

OPTIMISATION OF A HIGH SPEED 3 CYLINDER USING THE RICARDO WAVE ENGINE DEVELOPMENT SOFTWARE

ADVANCED COMPUTATIONAL METHODS - RICARDO WAVE

SUPERVISION

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BEng Motorcycle Engineering

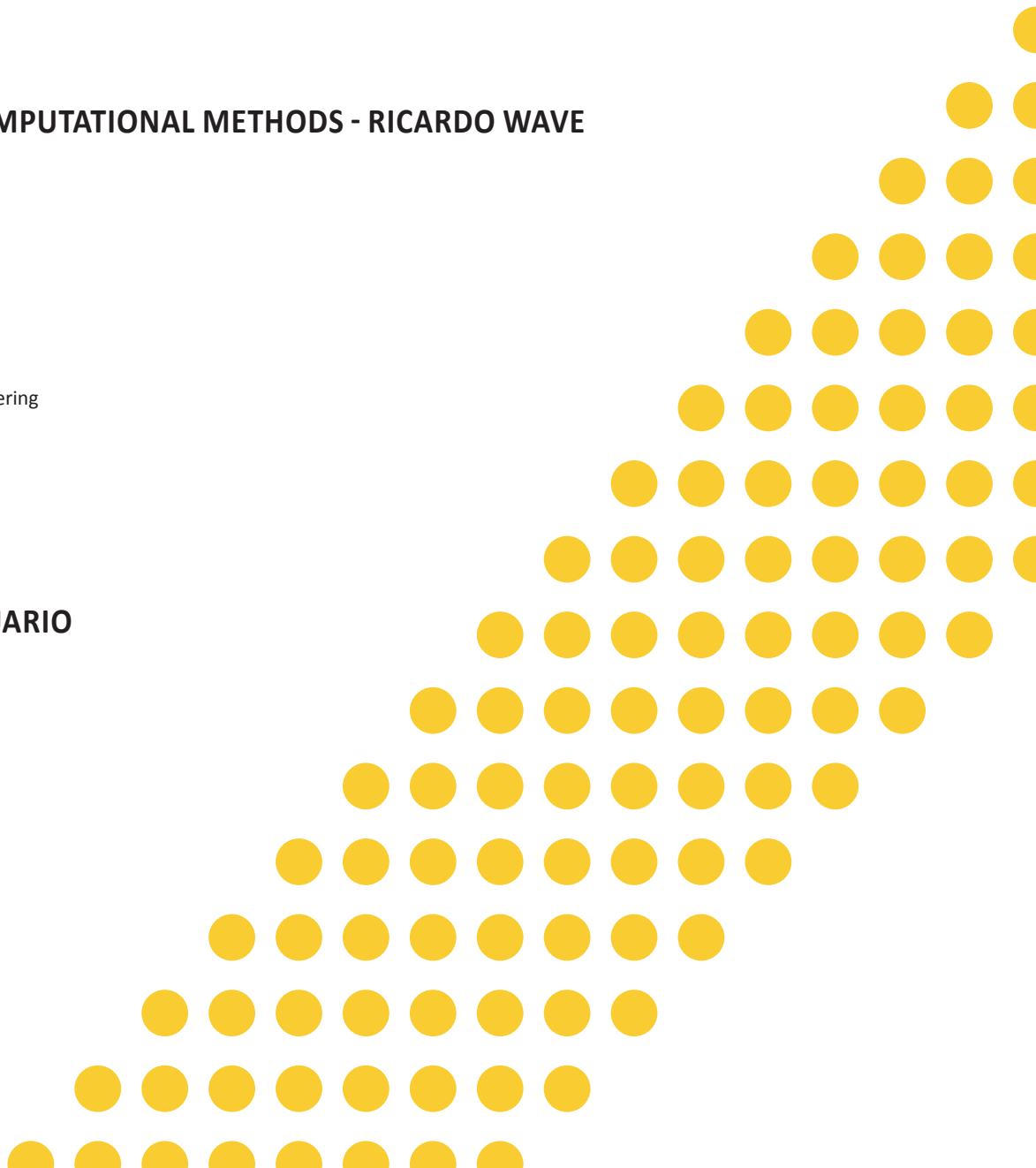
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Semester 1

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1 INTRODUCTION

The following assessment was developed for the module of Advanced Computational Methods – Wave option of the third year – level 6 of the Motorcycle Engineering Degree.

The aim of the presented work is to develop an engine model, for a high speed 3-cylinder motorcycle, capable of predicting the engine performance characteristics using the Ricardo WAVE engine development software.

Recurring to real pressure data from the engine supplied for specific RPM values, as well as theoretical and practical methods studied in previous modules, the engine model will be created, which – depending on the results obtained – can then be generalized for the remaining RPM range of the engine being studied.

Success will be measured by how accurate the results from the engine model are. Once the combustion and performance characteristics of the model match the ones from the real data provided and the model limitations are known, this model could then be generalized for the remaining RPM range and be used to introduce engine changes and then analyse how these reflect in its performance output.

2 ASSIGNMENT METHODOLOGY

For a better understanding of the work developed, the following assignment was divided in 4 main parts.

In *Part 1 – Real Data*, the author was proposed to analyse real cylinder pressure data provided from a Triumph 675 engine. Through the use of some theoretical methods, in a excel file, it was possible to calculate the combustion characteristics of the engine being analysed.

Combustion results, such as the mass of fuel burnt per degree of crank angle, the polytropic index for compression and expansion, the beginning and duration of the combustion, as some others, are calculated and plotted in this Chapter.

Later on, these results will then be used to feed the simulation model developed to get the most accurate performance output, and in some cases, be used to validate the solutions obtained from the model.

In *Part 2 – Stock WAVE Model*, the author ran the WAVE model provided for the assignment adding the camshaft and flowbench data available to allow it to run correctly. The results were then compared against the results calculated in *Part 1 – Real Data*.

In *Part 3 – Optimised WAVE Model*, all the combustion and performance variables calculated in *Part 1 – Real Data* were introduced into the WAVE model provided. The results were once more compared against the results calculated in *Part 1 – Real Data* and a conclusion was drawn regarding the accuracy of the WAVE model results when the model is fed by values retrieved from real data.

In *Part 4 – Refined WAVE Model*, the limitations of the software are discussed and some changes are introduced to the existent model in order to reduce the performance output errors between the WAVE model and the real engine.

3 PART 1 – REAL DATA

A set of cylinder pressure data and burned rate percentage for a Triumph Daytona 675cc was provided for the development of this assignment. The data available was related to the following RPM values: 10250, 13000 and 14400.

The data provided was then used to calculate certain combustion parameters of the engine being studied, that will be essential to feed the WAVE model and help validate its results and, consequently, the model itself.

At first, with access to the Triumph engine datasheet and the pressure data provided (identified by the colour grey below), a table was created, table. 1, where per all crank degree parameters as Volume, Polytropic Index, Combustion Temperature and Work Done were calculated (identified by the colour blue below).

Table 1. Preliminary Data analysis

FROM DATA			14400 RPM								
CALCULATED											
			DEGREE	VOL (CC)	logV	P	logP	n	dn	T (K)	WD
Comum Data											
Bore	0,076	m	-360	19,2315	2,95655	0,703155	-0,35218	-16,6304	-3,451703		0,000934
Stroke	0,0496	m	-359	19,24478	2,95724	0,695129	-0,36366	-20,0821	12,404914		0,0039
Conrod	0,1046	m	-358	19,30089	2,960151	0,655654	-0,42212	-7,67722	4,9937953		0,006485
Comp. Ratio	12,7		-357	19,3998	2,965263	0,630423	-0,46136	-2,68343	3,4325725		0,008931
Lambda	0,9		-356	19,54146	2,972538	0,618234	-0,48089	0,749143	-4,674368		0,011397
Ncyllinders	3		-355	19,72581	2,981928	0,622598	-0,47385	-3,92522	2,4437137		0,014129
Capacity	675,025	cc	-354	19,95275	2,993367	0,595261	-0,51876	-1,48151	2,2382716		0,016038
Density Air	1,167	Kg/m3	-353	20,22218	3,00678	0,583549	-0,53863	0,756761	-0,459216		0,018194
R	286,9	J/Kg.K	-352	20,53396	3,02208	0,590345	-0,52705	0,297544	-1,492332		0,020898
Swept Volume	225,008	cc	-351	20,88796	3,039173	0,593355	-0,52196	-1,19479	1,1587189		0,023499
Clearance Volume	19,23	cc	-350	21,28398	3,057955	0,580188	-0,5444	-0,03607	0,9015106		0,025405
Total Volume/Cyl	2,44E-04	m3	-349	21,72186	3,078319	0,579762	-0,54514	0,865442	-1,6896		0,027801
			-348	22,20138	3,100155	0,590822	-0,52624	-0,82416	1,3711688		0,030778
			-347	22,72231	3,123347	0,579636	-0,54535	0,547011	-0,196235		0,032581
			-346	23,2844	3,147784	0,587436	-0,53199	0,350776	-0,234764		0,035422
			-345	23,88739	3,173351	0,592728	-0,52302	0,116012	-0,932005		0,038148
			-344	24,53099	3,199937	0,594559	-0,51994	-0,81599	-0,480172		0,040662
			-343	25,21489	3,227435	0,581367	-0,54237	-1,29616	1,3007775		0,042084
			-342	25,93877	3,255739	0,560425	-0,57906	0,004613	-0,224324		0,042789

Calculated columns approach:

- logV, logP, n – Calculation of the polytropic index, n, for compression and expansion using the natural logarithm of V and P;

$$n = \frac{\log P_2 - \log P_1}{\log V_1 - \log V_2}$$

- dn - Rate of change of the polytropic index in respect to crank angle, allowing the more accurate determination of the value of the polytropic indexes for each RPM;

- T (k) – Gas temperature during the combustion process, given by:

$$T = \frac{PV}{\rho \cdot Total\ Volume \cdot R}$$

- WD – Work Done by gas inside the cylinder;

$$WD = PdV$$

These values calculated above were then used to identify more in-cylinder parameters and characteristics of the engine being studied, as it is stated in the following tables and plots presented below.

Table 2. Burn duration and m and a constants of the Wiebe function

	14400	13000	10250	Notes
MFB	Deg (°)	Deg (°)	Deg (°)	
0	-59	-59	-59	
0,1	-8	-4	-4	10% MFB
0,9	21	25	22	90% MFB
1	39	39	39	
Δ	29	29	26	
Using CFTool	m	5,848	6,271	6,753 CFTOOL
	a	9,506	7,942	10,77 CFTOOL

It was important to very well define the results from the table above, table 2., because they will be used as inputs afterwards in the WAVE model. The MFB values were taken from the data provided and the Wiebe constants were defined using the curve fitting tool from MATLAB, as shown below.

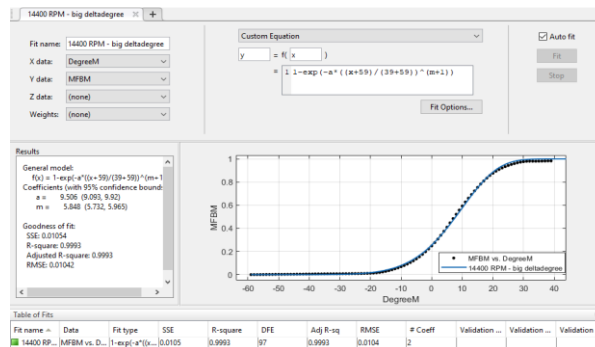


Figure 1. Matlab curve fitting tool for 14400RPM

Afterwards, another table was calculated, with an overall analysis of the Triumph engine performance characteristics for the specific RPM values being analysed. The results presented will be of extreme importance in order to compare and validate the WAVE model against the real data.

Table 3. Overall performance analysis of real engine

	RPM		
FROM DATA	10250	13000	14400
Work Done by Pump (J)	-7,54	-15,41	-20,18
Work Done by Comb (J)	332,19	336,35	318,69
Work Done by Gas (J)	324,65	320,94	298,52
Indicated Power (kW)	83,19	104,31	107,47
BRAKE POWER			
Work Done engine (J)	298,93	288,03	
Brake Power (kW)	76,60	93,61	
FRICTION			
Work Done by friction (J)	25,73	32,91	
Power Loss (kW)	6,59	10,70	
TORQUE (Nm)			
Gas Torque	77,51	76,62	71,27
Friction Torque	6,14	7,86	0,00
Brake Torque	71,36	68,76	0,00
MEP (bar)			
PIMEP	-0,33	-0,68	-0,90
GIMEP	14,76	14,95	14,16
NIMEP	14,43	14,26	13,27
BMEP	13,29	12,80	0,00
FMEP	1,14	1,46	0,00

Some considerations from Table. 3 Overall analysis of real engine:

- Indicated Power is given by:

$$P_i = \frac{WD \times RPS}{(\text{number of crank revolutions for each power stroke per cylinder})} \times \text{number of cyl}$$

- Brake Power values were extracted from a power dyno chart of the stock Triumph 675 engine; It wasn't possible to get power values for 14400RPM because in all the power charts available the engine never reached those engine velocities;
- After the considerations above, it was possible to calculate the Power Loss by Friction:

$$\text{Power Loss} = \text{Indicated Power} - \text{Brake Power}$$

- The mean effective pressure, MEP, is an important measure that represents the engine capacity to do work and it is independent of engine capacity, being one of the most used parameters when comparing engines performances;

$$MEP = \frac{Wi(Work\ Done)}{VolumeS}$$

Where,

$$NIMEP = GIMEP + PMEP$$

$$BMEP = NIMEP - FMPEP$$

The resulting plots from this part of the assignment will be presented in the following chapters in order to be used as a validation method of the WAVE model developed.

4 PART 2 – STOCK WAVE MODEL

In this chapter the WAVE model provided for the assignment, with the addition of camshaft and flowbench data available to allow it to run correctly, was run.

The results were then compared and plotted against the results obtained in chapter 3 *PART 1 – REAL DATA*.

4.1 CONSIDERATIONS PRIOR TO THE RUN

- Set up of Triumph Daytona 675 engine on Ricardo WAVE software;

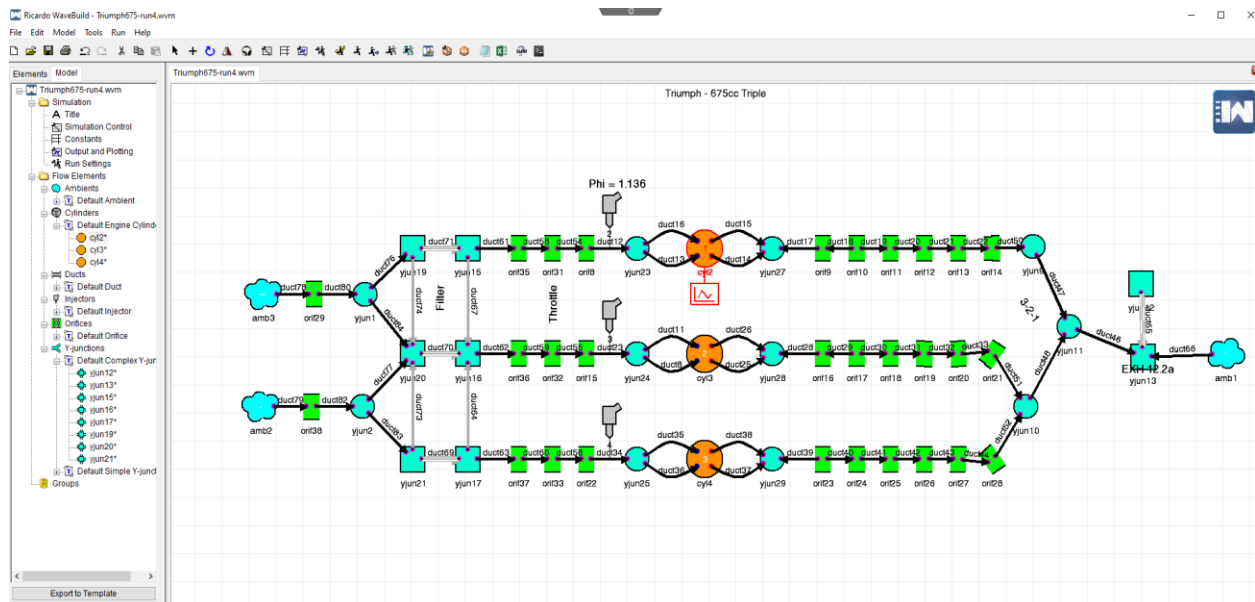


Figure 2. Engine set up in Ricardo WAVE software

- The module needs to be checked for error by pressing the icon “Run Input Check”;
- If no failure features were found, the model could then be run by pressing the icon “Run Screen Mode”;

4.2 RESULTS

Four different plots were compared for the three different rpm values: Pressure Vs Volume; MFB Vs Crank Angle; Pressure Vs Crank Angle and Cylinder Temperature Vs Crank Angle.

The author was able to export the results worked out from the real data in the Excel file, to the WAVE software, making it possible to analyse the plots and take conclusions about the accuracy of the combustion process of the stock model provided.

Once this is the model provided with no changes made by the author, the conclusions presented below are not definitive but will serve as a good example of practice used by the author to compare the real data against the WAVE model.

4.2.1 PLOTS

For 10250 RPM:

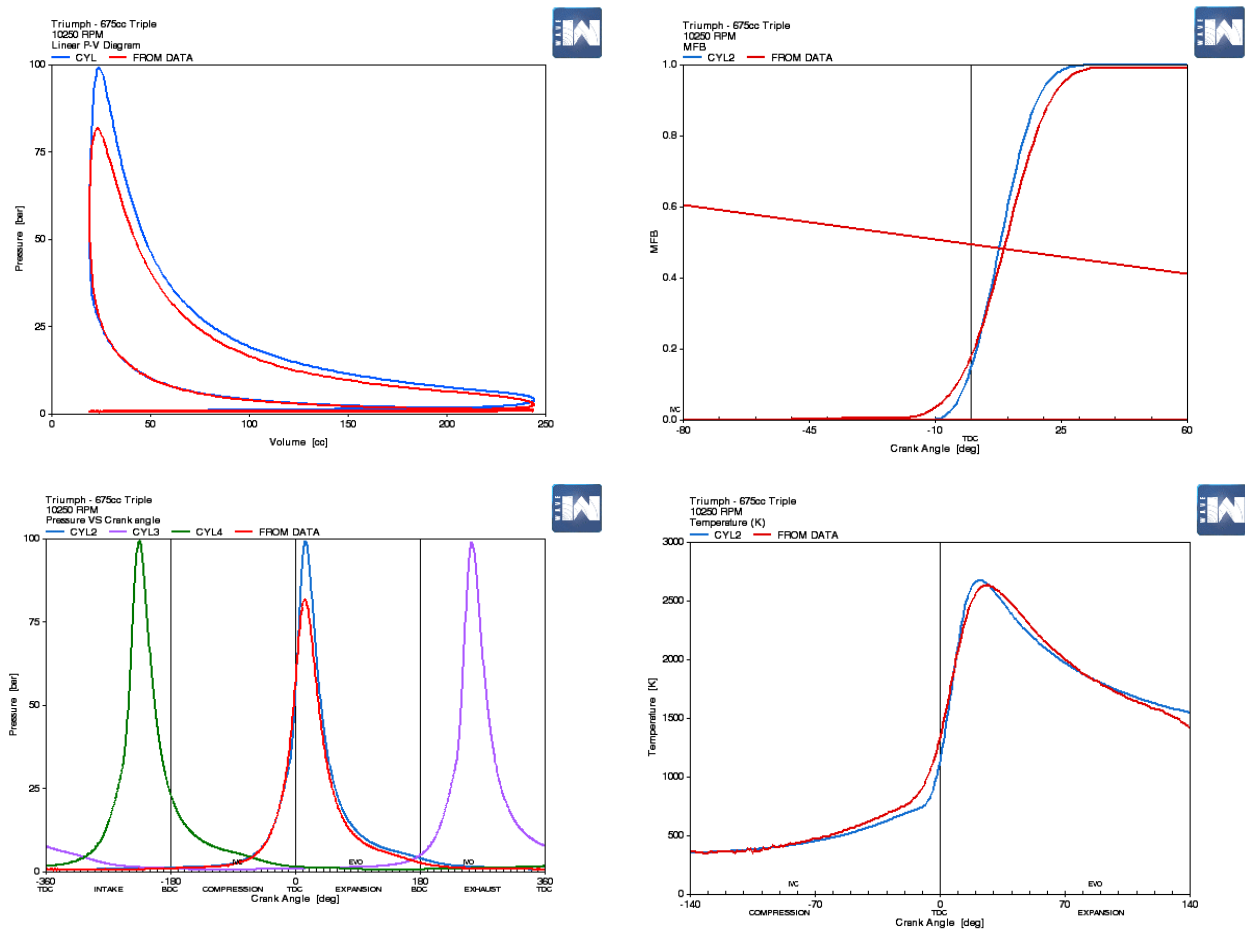


Figure 3. Stock Run Plots at 10250 RPM from Ricardo WAVE

From the Pressure-Volume diagram, it was observed that the section related to the engine Power Stroke of the model wasn't matching the results from the data. The pressure values were superior to the ones from data.

For 13000 RPM:

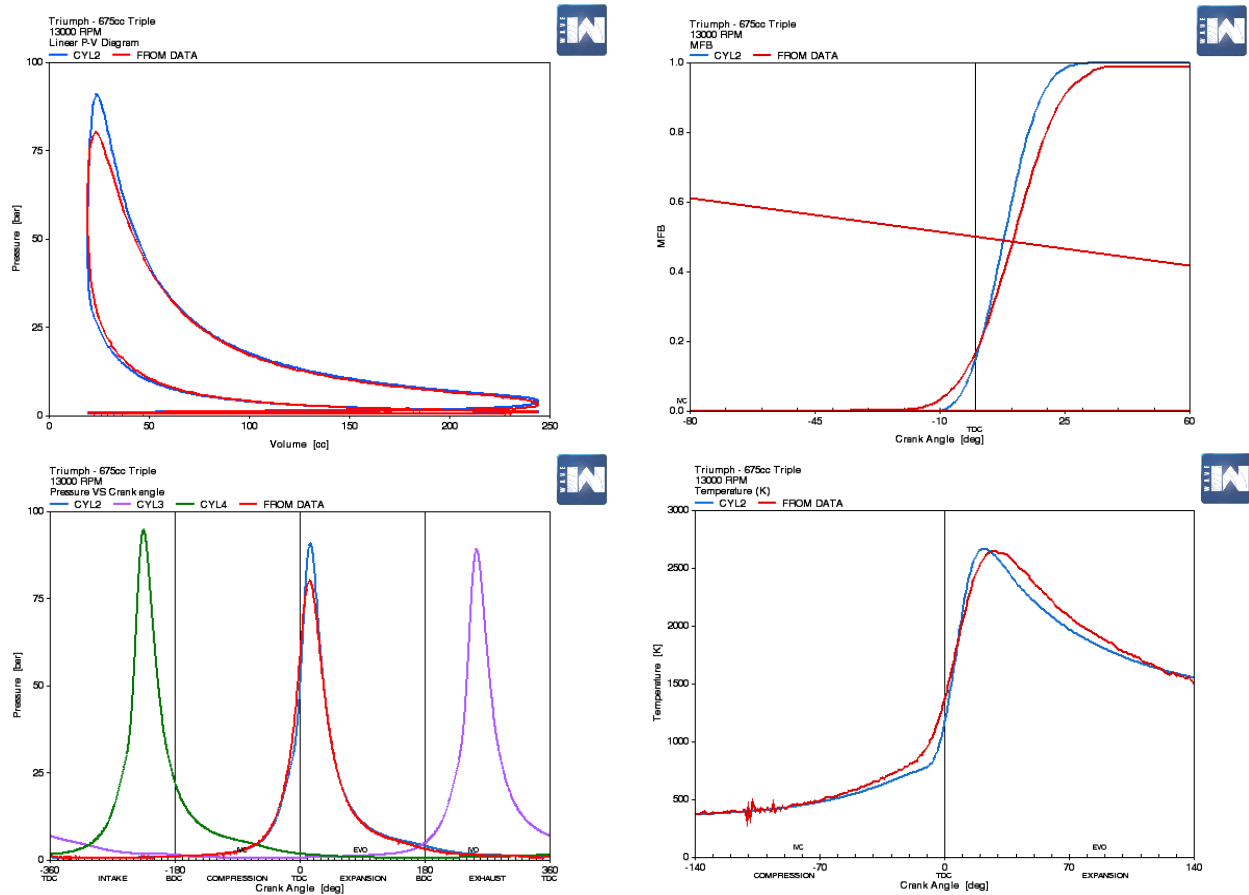


Figure 4. Stock Run Plots at 13000 RPM from Ricardo WAVE

For 13000 RPM it was observed a similar trend as the one from 10250 RPM, even though the pressure difference was a bit inferior. A more detailed analysis will follow in the next chapters, where the model will already have inputs calculated from real data that will result in more accurate results from the model.

For 14400 RPM:

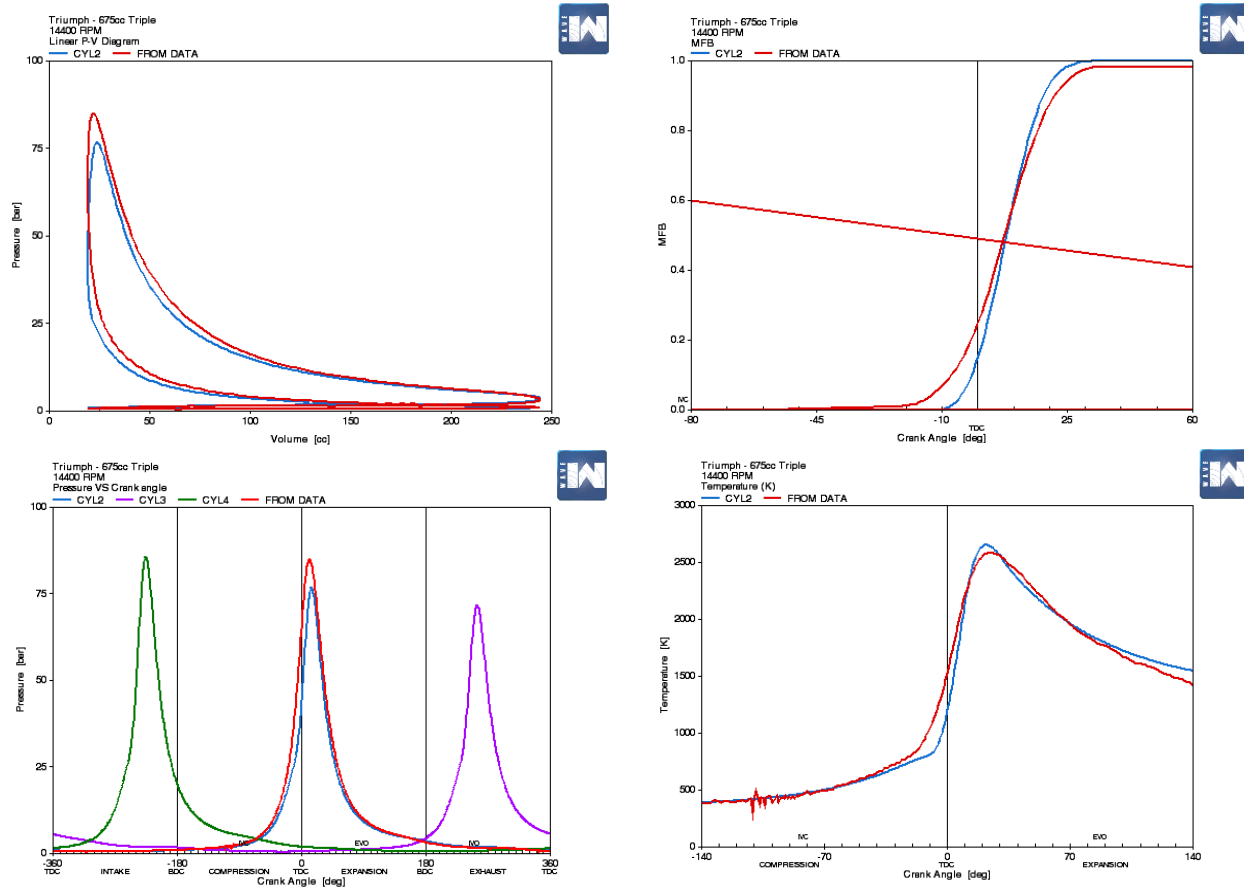


Figure 5. Stock Run Plots at 14400 RPM from Ricardo WAVE

Even though there is a resemblance between the results from data and the WAVE model, the author decided not to consider the 14400 RPM in further analysis due to the inexistence of real power values for this RPM value. This RPM value is outside the RPM range of the engine being analysed.

4.2.2 OVERALL PERFORMANCE

Table 4. Stock Run Overall Performance

STOCK RUN				
10250 RPM				
POWER (kW)	FROM DATA	RICARDO WAVE	ERROR	
Indicated Power	83,19	99,67	19,8%	
Brake Power	76,60	83,81	9,4%	
TORQUE (Nm)				
Indicated Torque	77,51	92,85	19,8%	
Friction Torque	6,14	14,77	140,5%	
MEP (bar)				
GIMEP	14,76	17,77	20,4%	
PIMEP	-0,33	-0,48	44,7%	
NIMEP	14,43	17,29	19,8%	
FMEP	1,14	2,75	140,5%	
BMEP	13,29	14,54	9,4%	
EFFICIENCY (%)				
Volumetric efficiency	0,9	1,30	44,6%	

13000 RPM				
POWER (kW)	FROM DATA	RICARDO WAVE	ERROR	
Indicated Power	104,31	112,62	8,0%	
Brake Power	93,61	89,28	-4,6%	
TORQUE (Nm)				
Indicated Torque	76,62	82,73	8,0%	
Friction Torque	7,86	17,15	118,2%	
MEP (bar)				
GIMEP	14,95	16,27	8,8%	
PIMEP	-0,68	-0,87	26,4%	
NIMEP	14,26	15,40	8,0%	
FMEP	1,46	3,19	118,2%	
BMEP	12,80	12,21	-4,6%	
EFFICIENCY (%)				
Volumetric efficiency	0,9	1,09	21,4%	

As it can be observed in the table above, there are several sources of errors in the provided model. For both cases, a big error percentage associated to Friction can be easily observed, with percentages superior to 100%. The percentage errors in the Indicated Power and PIMEP also indicate that the combustion process is not that well defined in the model provided.

Once again, the 1440 RPM table was not presented due to the lack of Brake Power figures for the real engine.

The Ricardo Wave values used in the table above were supplied from a Summary Data Table provided by Wave Post:

Table 5. Stock Run Summary Table from Ricardo WAVE

Default Summary Data - Triumph75-stock-run-sum, Data for engine

Name: Data for engine

Results Table

1	Engine speed	rpm	10249	12599	14400
2	Case	-	1	2	3
3	Subcase	-	0	0	0
4	Case title	-	Case 1	Case 2	Case 3
5	Stoichiometric A/F	-	14.5569	14.5569	14.5569
6	Trapped A/F	-	12.8591	12.8607	12.8638
7	Mass Airflow	kg/hr	314.615	334.902	303.76
8	Pseudo-volumetric effci	kg/hr/rpm	0.0306942	0.0257617	0.0210944
9	Auxiliary Power	kW	0	0	0
10	BMEP	bar	14.5361	12.2085	9.12409
11	Brake Power	kW	83.8131	89.2778	73.9078
12	Brake specific CO emissi	g/kW/hr	0	0	0
13	BSFC	kg/kW/hr	0.291924	0.29166	0.319472
14	Brake specific unburned	g/kW/hr	33.2013	11.5544	7.35139
15	Brake specific NO2 emiss	g/kW/hr	0	0	0
16	Charging efficiency	-	1.1866	1.06982	0.869168
17	Delivered efficiency	-	1.33818	1.11348	0.895249
18	Total delivered efficien	-	1.33818	1.11349	0.895261
19	Combined Displacement	m³	0.000475025	0.000475025	0.000475025
20	Brake thermal engine eff	%	28.5595	28.5853	26.0968
21	EGR	-	8.31409e-007	1.40136e-005	-9.26254e-006
22	FMEP	bar	2.74949	3.19244	3.36563
23	Friction Energy Loss	%	5.40198	7.47487	9.62642
24	Friction torque	Nm	14.7694	17.1488	18.0792
25	Fuel mass flow	kg/hr	24.467	26.0382	23.6115

OK Apply Cancel

5 PART 3 – OPTIMISED WAVE MODEL

In this Chapter, all the combustion and performance variables calculated in chapter 3 *Part 1 – Real Data* were introduced into the WAVE model provided.

At this point, with a combustion process well defined in the WAVE model, the results from the model will be compared against the results calculated in Part 1 – Real Data and it will be observed if further changes and assumptions need to be performed in order to increase the accuracy of the results.

The results from the optimized model were then plotted and compared against the results obtained in chapter 3 *Part 1 – Real Data*.

5.1 CONSIDERATIONS PRIOR TO THE RUN

- Ambient Panel:
 - Temperature was changed from 300 K to 293 K;
 - Pressure was changed from 1.065 bar to 1 bar;
 - Discharge coefficient was set as AUTO for the current model;
- Injectors:
 - FARD was changed from 0.08 to 0.08(3);
- Cylinder Panel:
 - Conrod length was corrected from 98mm to 104.6mm;
 - Compression Ratio changed from 12.65 to 12.7;
 - Inlet and exhaust valve timings changed to match valve timings stated by the factory;

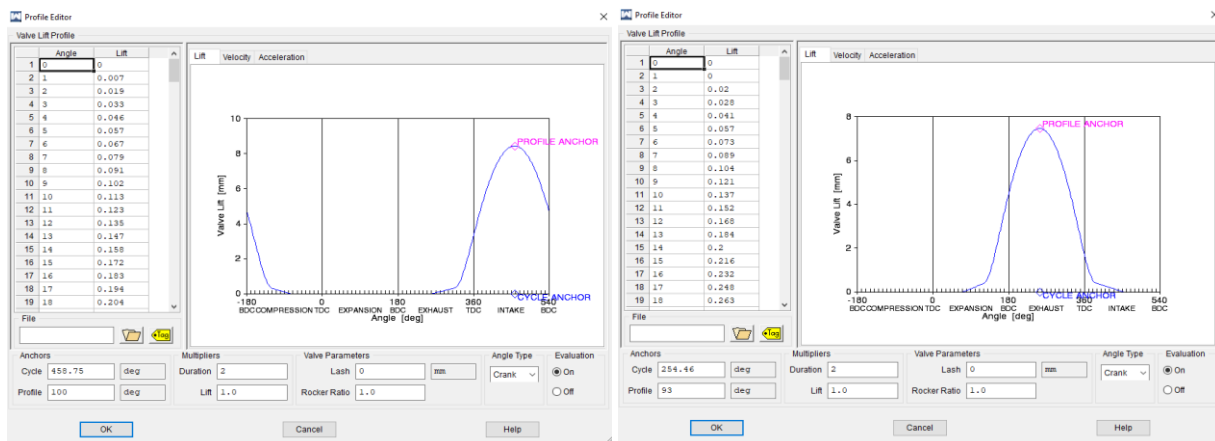


Figure 6. Valves settings from Ricardo WAVE

- The Wiebe function was corrected, introducing the parameters calculated in chapter 3 for each RPM value;

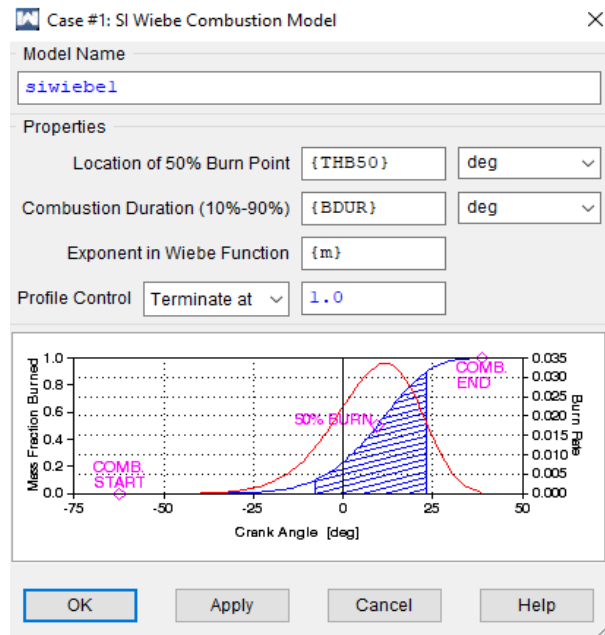


Figure 7. Wiebe function settings from Ricardo WAVE

5.2 RESULTS

Four different plots were again compared, but now just for two different rpm values (10250 RPM and 13000 RPM): Pressure Vs Volume; MFB Vs Crank Angle; Pressure Vs Crank Angle and Cylinder Temperature Vs Crank Angle.

The author was able to export the results worked out from the real data in the Excel file, to the WAVE software, making it possible to analyse the plots and take conclusions about the accuracy of the combustion process of the OPTIMISED MODEL.

5.2.1 PLOTS

For 10250 RPM:

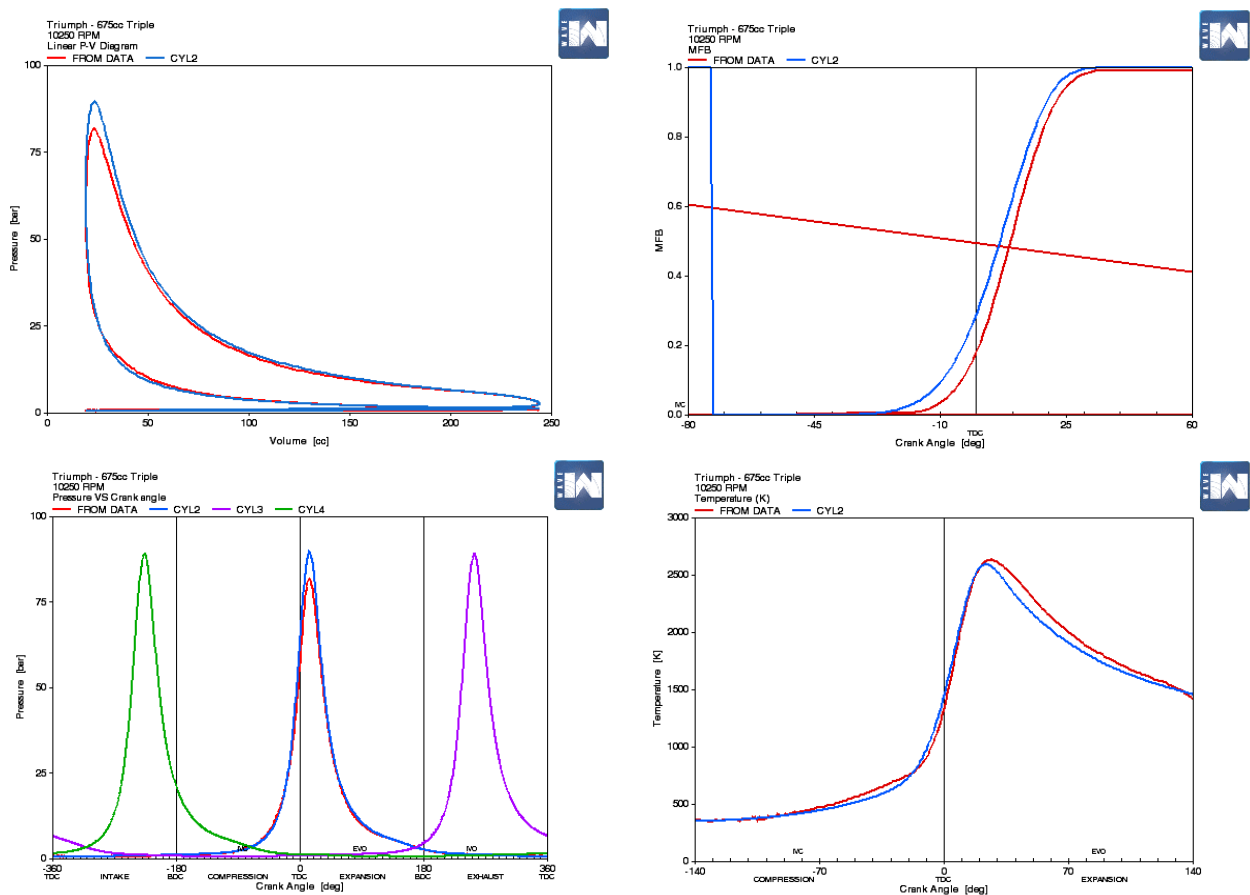


Figure 8. Optimised Run Plots at 10250 RPM from Ricardo WAVE

From the analysis of the plots above, even though the results were substantially improved when compared to the provided model (chapter 4.2.1), it can be observed that the Wiebe function has a slight offset for 10250 RPM. The maximum pressure difference is 81.9 bar for the real data versus 89.5 bar for the model. Changing the 50% burn point in the model could possibly correct this, as well as correct the difference of pressure observed in the other plots. This change will be performed in chapter 6.

For 13000 RPM:

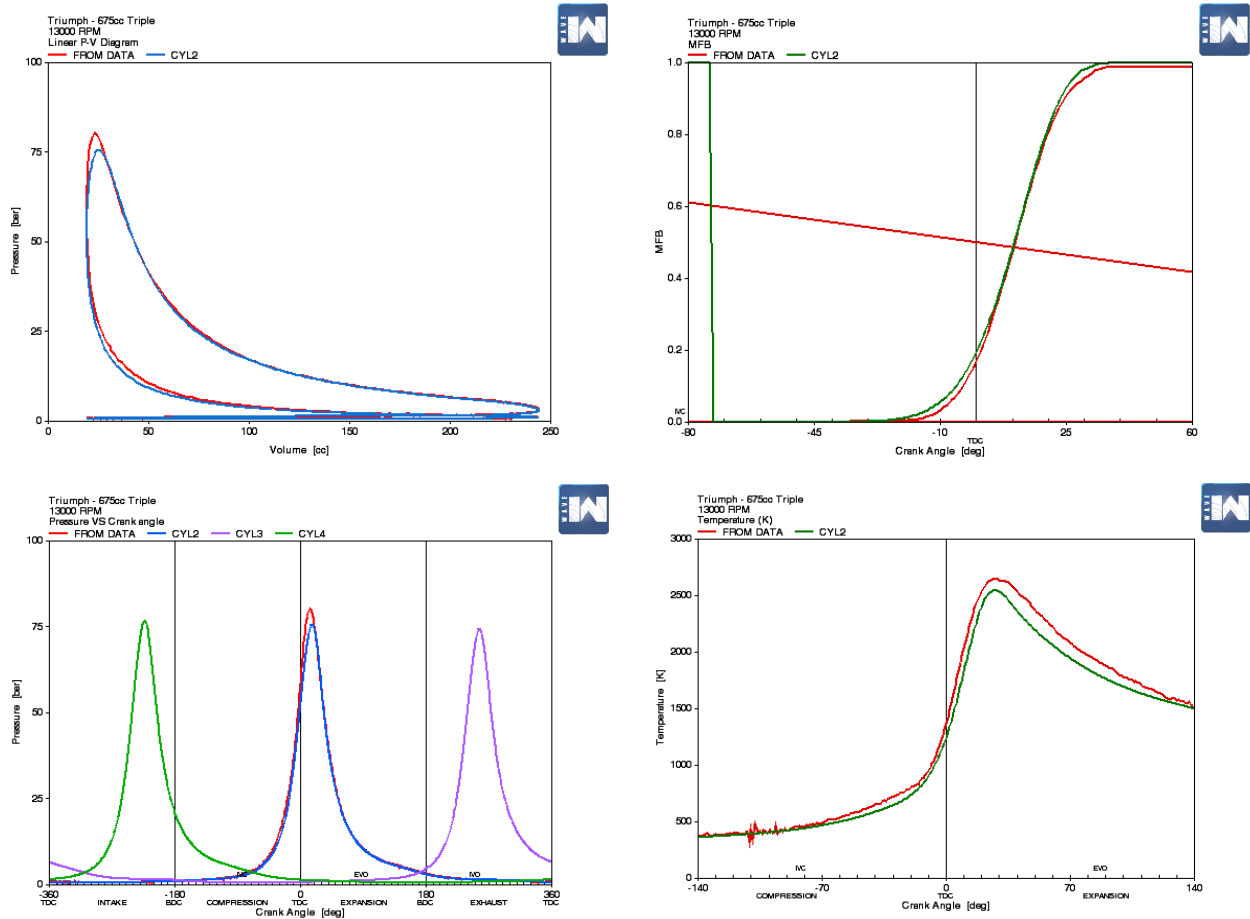


Figure 9. Optimised Run Plots at 13000 RPM from Ricardo WAVE

For 13000 RPM the differences between the results from real data versus the results from the model were reduced. The maximum pressure difference is 80.2 bar for the real data versus 75.6 bar for the model.

The combustion process is well defined and only through the analysis of the plots above, it can be stated that the model is close to be validated for 13000RPM, which is close to maximum power of the given engine (12600 RPM).

Results from the next table will dictated how accurate the model is for maximum power values.

5.2.2 OVERALL PERFORMANCE

Table 6. Optimised Run Overall Performance from Ricardo WAVE

OPTIMISED RUN				
10250 RPM				
POWER (kW)	FROM DATA	RICARDO WAVE	ERROR	
Indicated Power	83,19	88,93	6,9%	
Brake Power	76,60	73,42	-4,1%	
TORQUE (Nm)				
Indicated Torque	77,51	82,86	6,9%	
Friction Torque	6,14	14,45	135,3%	
MEP (bar)				
GIMEP	14,76	15,73	6,5%	
PIMEP	-0,33	-0,30	-10,0%	
NIMEP	14,43	15,42	6,9%	
FMEP	1,14	2,69	135,3%	
BMEP	13,29	12,73	-4,1%	
EFFICIENCY (%)				
Volumetric efficiency	1	1,1199	12,0%	
13000 RPM				
POWER (kW)	FROM DATA	RICARDO WAVE	ERROR	
Indicated Power	104,31	104,54	0,2%	
Brake Power	93,61	81,90	-12,5%	
TORQUE (Nm)				
Indicated Torque	76,62	76,79	0,2%	
Friction Torque	7,86	16,63	111,6%	
MEP (bar)				
GIMEP	14,95	14,93	-0,1%	
PIMEP	-0,68	-0,63	-7,5%	
NIMEP	14,26	14,30	0,2%	
FMEP	1,46	3,10	111,6%	
BMEP	12,80	11,20	-12,5%	
EFFICIENCY (%)				
Volumetric efficiency	1	1,00642	0,6%	

As it can be observed in the table above, real good accuracy was achieved for both RPM values, proving that the overall performance of the model is matching the performance results from data.

There is still a big error percentage associated to Friction, with percentages superior to 100%. This error is then reflected when comparing the Brake Power output of the engine in a lower percentage. A change will be proposed in the next chapter, chapter 6, to improve this scenario.

The Indicated Power for 10250 RPM presents a small deviation that could be related to what was already observed in the previous plots, a slightly offset in the MFB curve.

As it was stated when analysing the plots for 13000 RPM, the combustion was well defined, being proven now by error percentages inferior to 1% for combustion related parameters (Indicated Power, GIMEP, NIMEP and volumetric efficiency).

6 PART 4 – REFINED WAVE MODEL

In this chapter, some final refinements were performed to reduce the error percentage between the model and the real data results in order to validate the model developed so far.

The MFB for 10250 RPM was addressed, hoping to improve the combustion correlation between the model and real data and the friction parameters in the model were tuned in order to reduce the error percentage in the two RPM values being analysed.

The results from the refined model were then plotted and compared against the results obtained in chapter 3 Part 1 – Real Data.

6.1 CONSIDERATIONS PRIOR TO THE RUN

- Cylinder Panel:
 - For 10250 RPM the location of 50% Burn Point was changed from 6.5° to 9.5°;
 - Friction of the overall model was reduced following the HELP file instructions from Ricardo WAVE software;

$$FMEP = ACF + BCF(P_{max}) + CCF(rpm * stroke/2) + QCF(rpm * stroke/2)^2$$

The use of the BCF term is to account for changes in P_{max} , which can be used to vary frictional losses across a range of engine loads. The CCF and QCF terms are used to account for changes in rpm, varying frictional losses across a range of engine speeds.

Case #1: Engine General Panel

Geometry

Operating Parameters

Scavenge

Combustion

Conduction

Heat Transfer

Turbulence and Flow

Head Geometry

Slaved Models

Configuration

No. of Cylinders3

Strokes per Cycle4

Engine TypeSpark Ignition

Displacement0.6750251

Friction Correlation

ACF0.25bar

BCF0.001

CCF300Pa*min/m

QCF0.2Pa*min^2/m^2

Figure 10. Refined Run Friction Settings from Ricardo WAVE

6.2 RESULTS

Four different plots were again compared for the two different rpm values (10250 RPM and 13000 RPM): Pressure Vs Volume; MFB Vs Crank Angle; Pressure Vs Crank Angle and Cylinder Temperature Vs Crank Angle.

The author was able to export the results worked out from the real data in the Excel file, to the WAVE software, making it possible to analyse the plots and take conclusions about the accuracy of the combustion process of the REFINED MODEL.

6.2.1 PLOTS

For 10250 RPM:

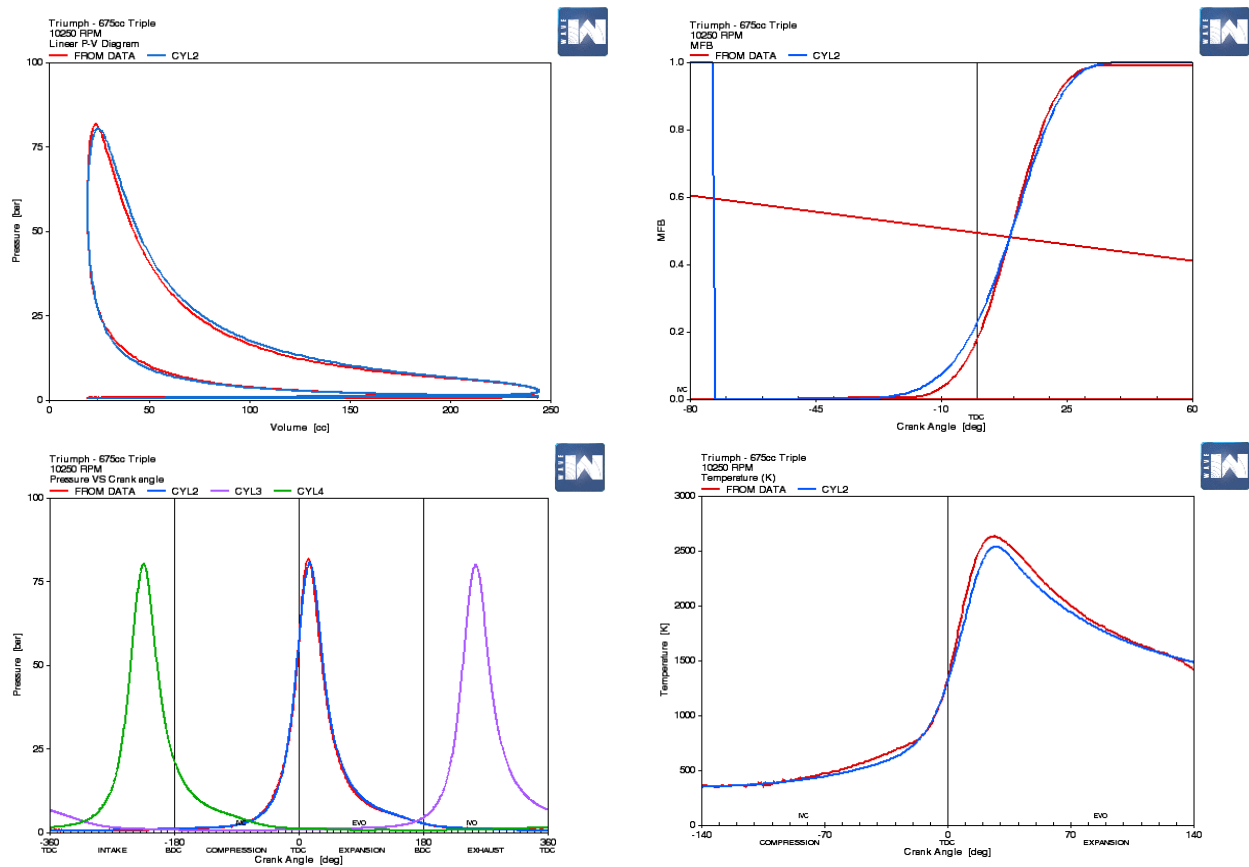


Figure 11. Refined Run Plots at 10250 RPM from Ricardo WAVE

From the analysis of the plots above, it can be observed that the change in the location of 50% Burn Point for 10250 RPM had a positive impact in the results. The PV diagram and the Pressure plots are matching the results, proving the validation of the combustion process in the model. The maximum pressure difference is 81.9 bar for the real data versus 80.5 bar for the model. The Overall performance comparison (chapter 6.2.2) now needs to be analysed in order to validate the model for this specific RPM value.

For 13000 RPM:

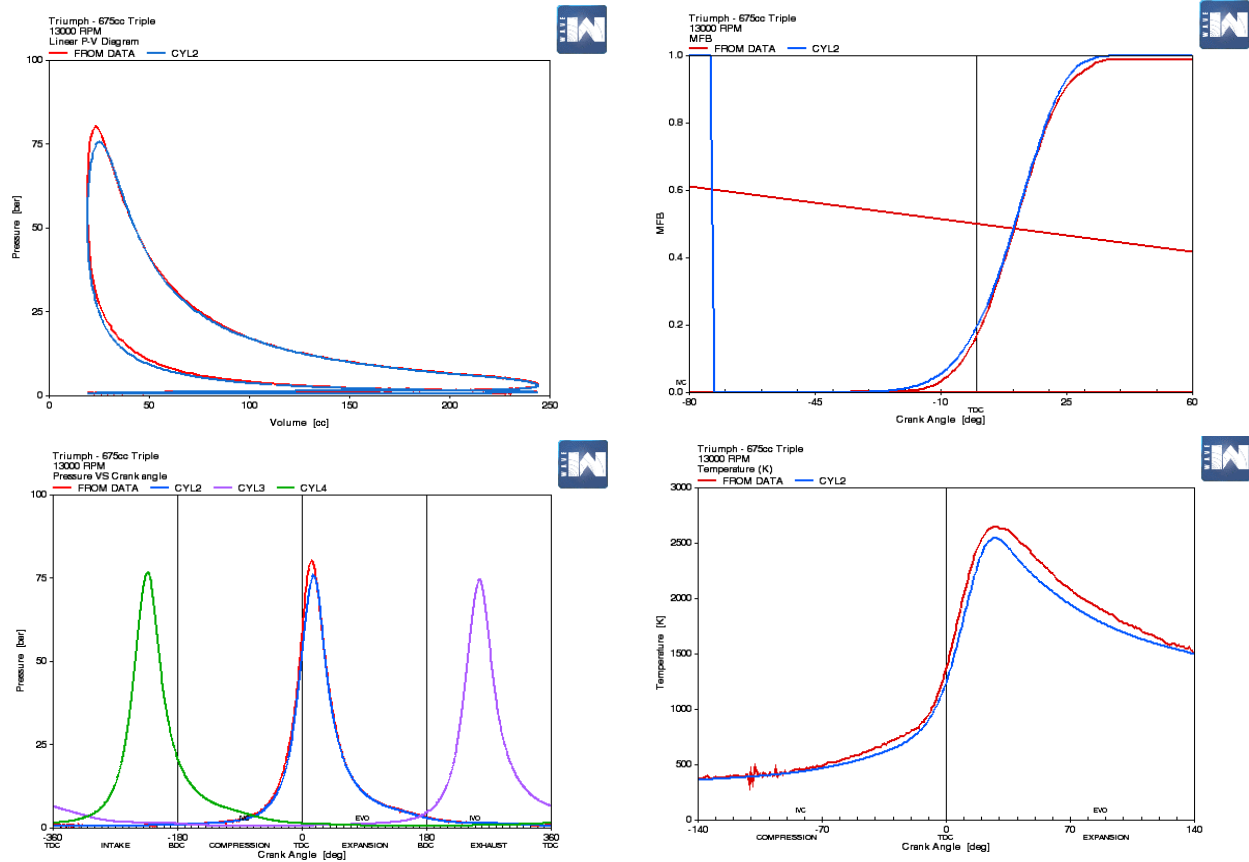


Figure 12. Refined Run Plots at 13000 RPM from Ricardo WAVE

For 13000 RPM the differences between the results from real data versus the results from the model were kept the same since the previous change in the model, chapter 5 – *Optimised WAVE Model*. The maximum pressure difference is 80.2 bar for the real data versus 75.6 bar for the model.

The changes performed for the refined model didn't affect the combustion process for 1300 RPM.

Results from the next table will dictate how accurate the model is in relation to its performance characteristics.

6.2.2 OVERALL PERFORMANCE

Table 7. Refined Run Overall Performance Comparison

REFINED RUN				
10250 RPM				
POWER (kW)	FROM DATA	RICARDO WAVE	ERROR	
Indicated Power	83,19	88,34	6,2%	
Brake Power	76,60	81,30	6,1%	
TORQUE (Nm)				
Indicated Torque	77,51	82,31	6,2%	
Friction Torque	6,14	6,56	6,9%	
MEP (bar)				
GIMEP	14,76	15,61	5,8%	
PIMEP	-0,33	-0,29	-12,7%	
NIMEP	14,43	15,32	6,2%	
FMEP	1,14	1,22	6,9%	
BMEP	13,29	14,10	6,1%	
EFFICIENCY (%)				
Volumetric efficiency	1	1,12088	12,1%	

13000 RPM				
POWER (kW)	FROM DATA	RICARDO WAVE	ERROR	
Indicated Power	104,31	104,62	0,3%	
Brake Power	93,61	93,64	0,0%	
TORQUE (Nm)				
Indicated Torque	76,62	76,85	0,3%	
Friction Torque	7,86	8,06	2,6%	
MEP (bar)				
GIMEP	14,95	14,94	-0,1%	
PIMEP	-0,68	-0,63	-7,4%	
NIMEP	14,26	14,31	0,3%	
FMEP	1,46	1,50	2,6%	
BMEP	12,80	12,81	0,0%	
EFFICIENCY (%)				
Volumetric efficiency	1	1,00682	0,7%	

As it can be observed in the table above, the accuracy of the results was improved from the previous model in Chapter 5, with the new changes implemented, proving that the overall performance of the model is matching the performance results from data.

With the changes performed, the error percentage associated to Friction, was reduced from more than 100% to 6.9 % and 2.6% at 10250 RPM and 13000 RPM respectively. With this improvement the brake power output from the WAVE model matches the one from the real engine perfectly at 13000 RPM, with an error of 0%.

With the refinement performed to the WAVE model it was possible to obtain a substantially close relation between the results output from the model versus the real data. It is observed from the table above an average error of around 6% for 10250 RPM and an average of less than 1% for 13000 RPM.

This small percentage of errors after the model refinement allow the author to validate the model developed.

7 CONCLUSION

This project allowed the author to develop an engine model, able to calculate the combustion and performance characteristics of a specific engine using Ricardo Wave engine development software.

Prior to get a final running model, it was required to obtain real data from the analysed engine and calculate some specific parameters through the use of theoretical formulas. These parameters were then used to feed the model in order to obtain the best possible results.

The model developed was successfully validated, the results obtained for specific RPM values matched by small error percentages the expected values from an analytical solution. This represents that the model developed will output coherent solutions even for different cases, different RPM values.

The model developed represents a powerful tool when performing engine simulations, because, once validated, it allows to perform different changes in an engine and obtain results in a really short period of time. In the engineering world, where engine development is a really expensive department of companies, where making changes and having problems in a real test engine would represent a big cost, the use of a simulation model represents quicker progress and cost saving.

8 BIBLIOGRAPHY

- Blair, G. P. (1999). *Design and Simulation of Four-Stroke Engines*. Warrendale, Pa: Society of Automotic Engineers, Inc.
- Heywood, J. B. (1988). *Internal Combustion Engine Fundamentals*. McGraw-Hill, Inc.